Future Mars Navigation Architecture

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Current, Planned and Proposed Architectures

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- Self-Navigation of Network Orbiters

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- Orbiters
- Approach/Departure
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- 2005 Mars Sample Return Orbiting Sample Canister
- 2005 Net Landers

Introduction

The current and planned Mars Navigation Architecture consists of several navigation measurement systems:

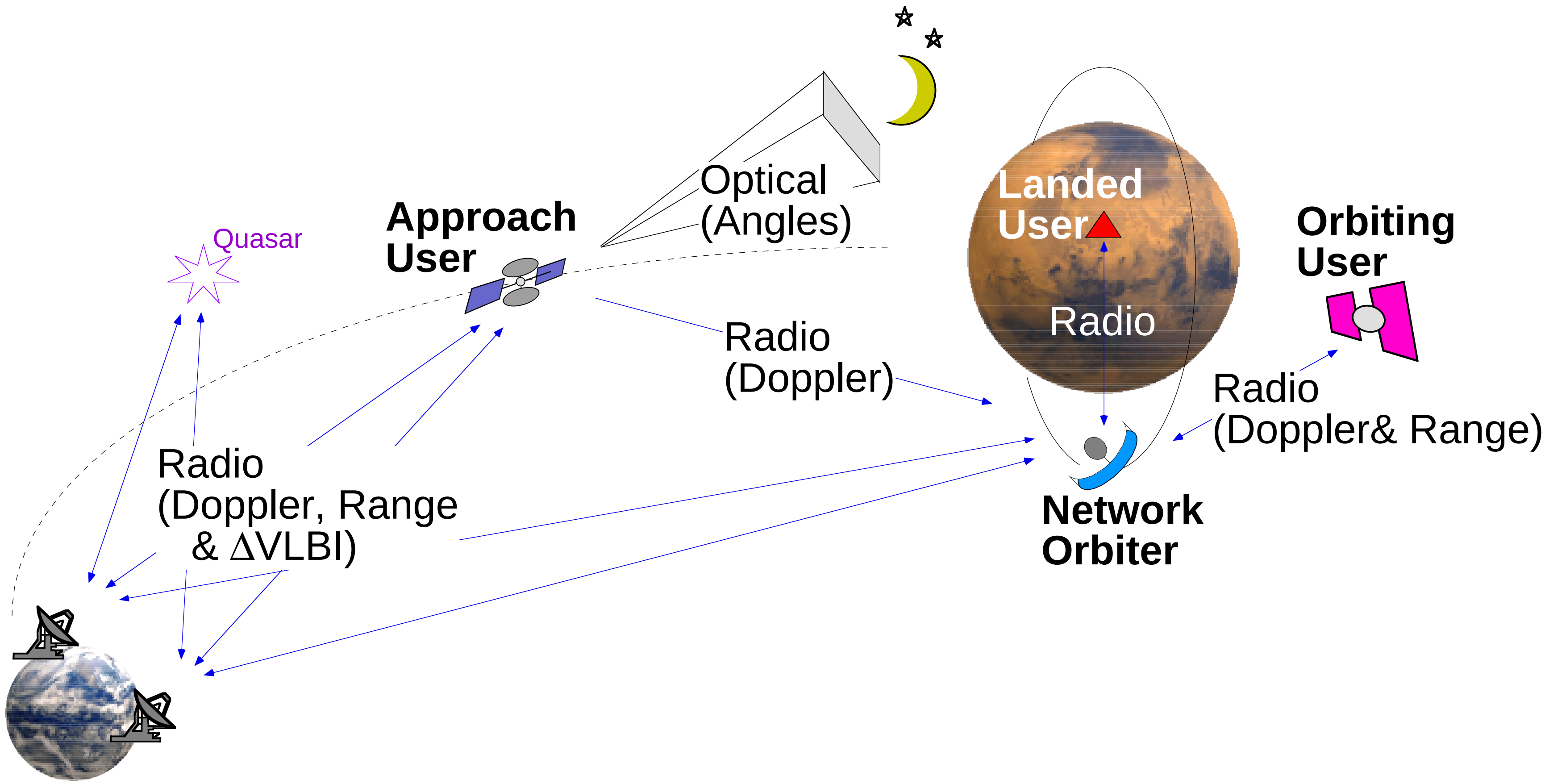
- Earth-Based radio doppler and range
- Earth-Based radio Differential Very Long Baseline Interferometry (ΔVLBI)
- In-Situ radio doppler and range with a Network of Mars orbiting spacecraft
- In-Situ optical with Mars moons Phobos and Deimos

Mars Navigation Architecture provides user services and performs self-navigation of Network orbiters

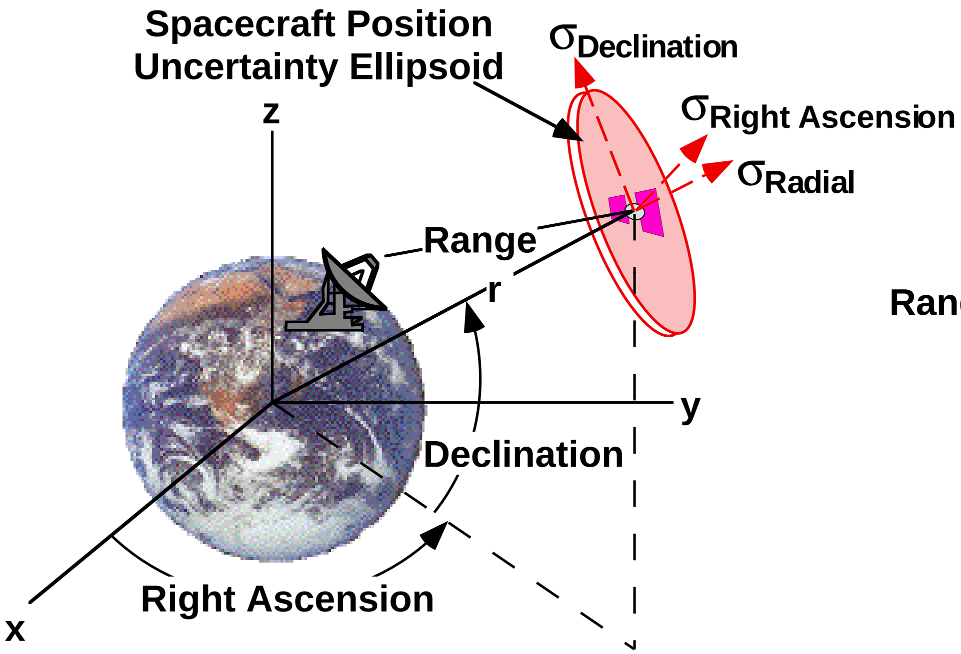
Navigation is defined as:

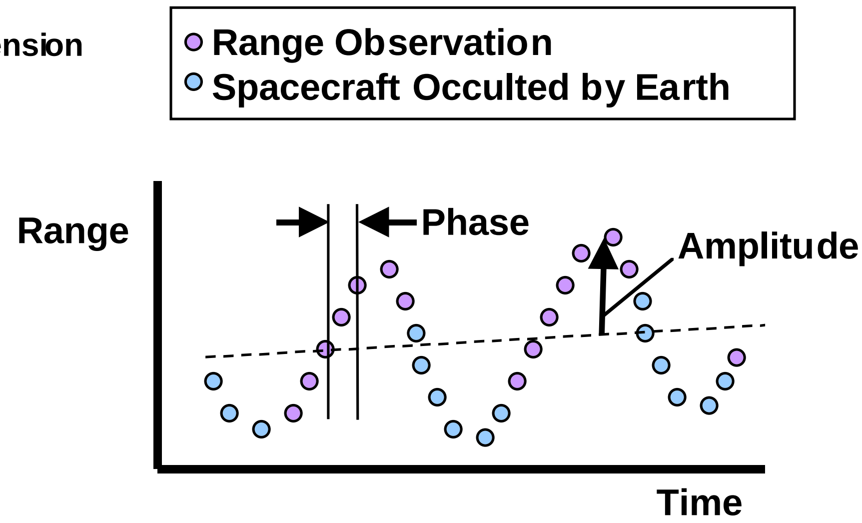
- Surface asset positioning
- Mars orbiting asset state determination (positions and velocities)
- Positioning for precision landing / atmospheric exploration
- Mars Network orbiter trajectory determination and control

Future Mars Navigation Architecture



Radial Direction Known Best from Traditional Navigation



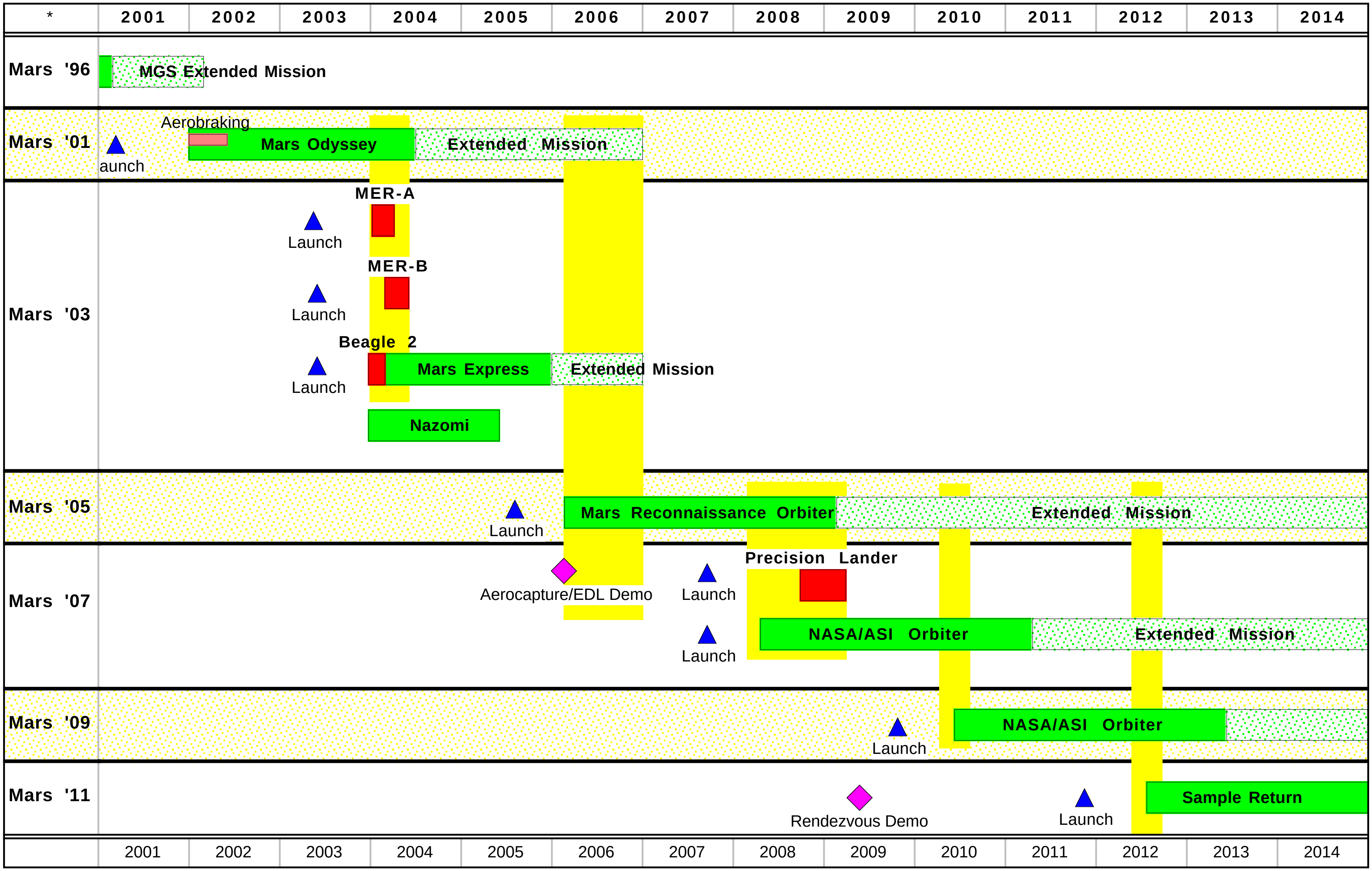


Radial Position is Derived from Mean Trend in Range Data

Declination is Derived from Amplitude of Range (or Doppler) Data

Right Ascension is Derived from Phase of Range (or Doppler) Data

Mars Missions



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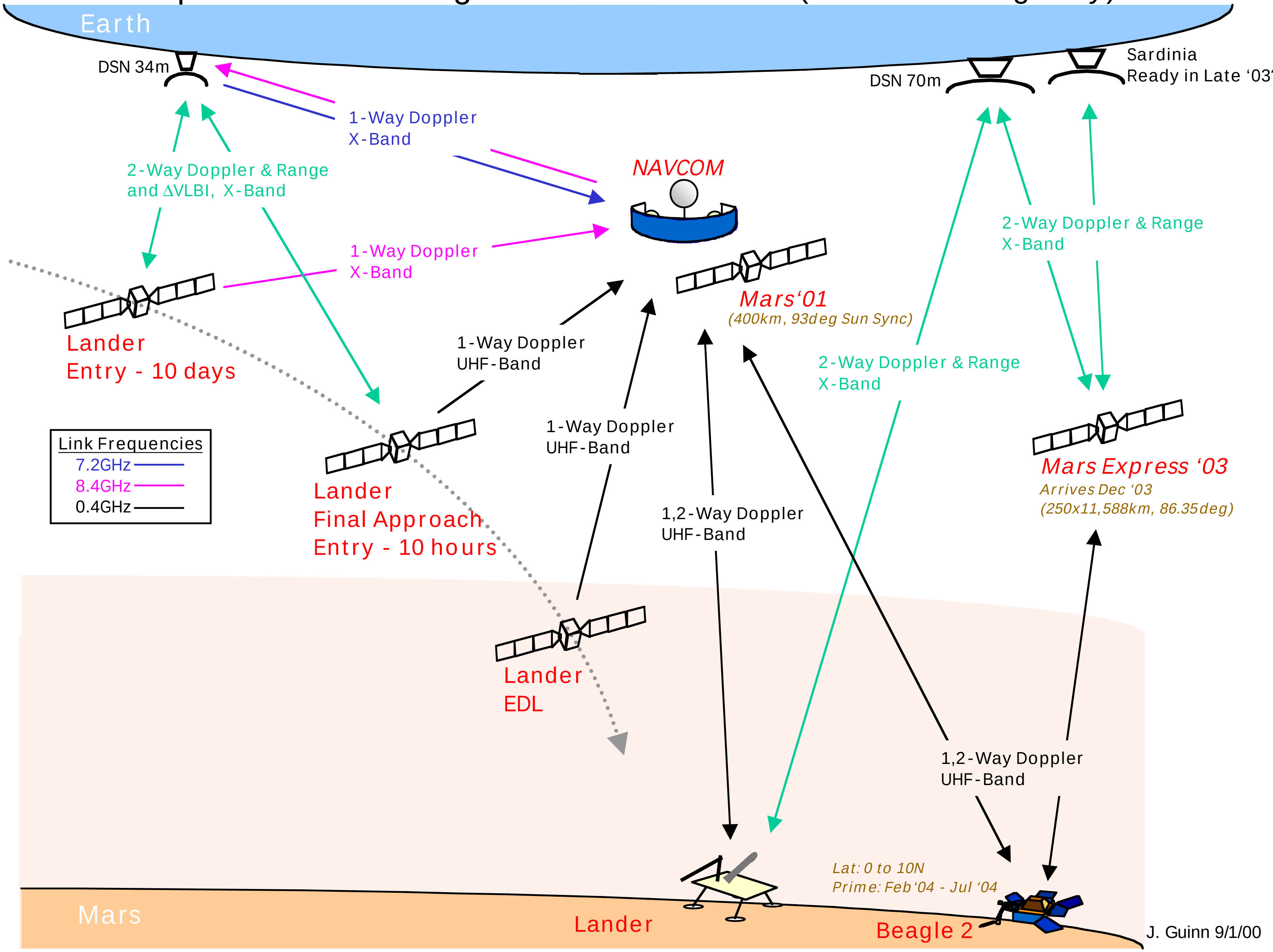
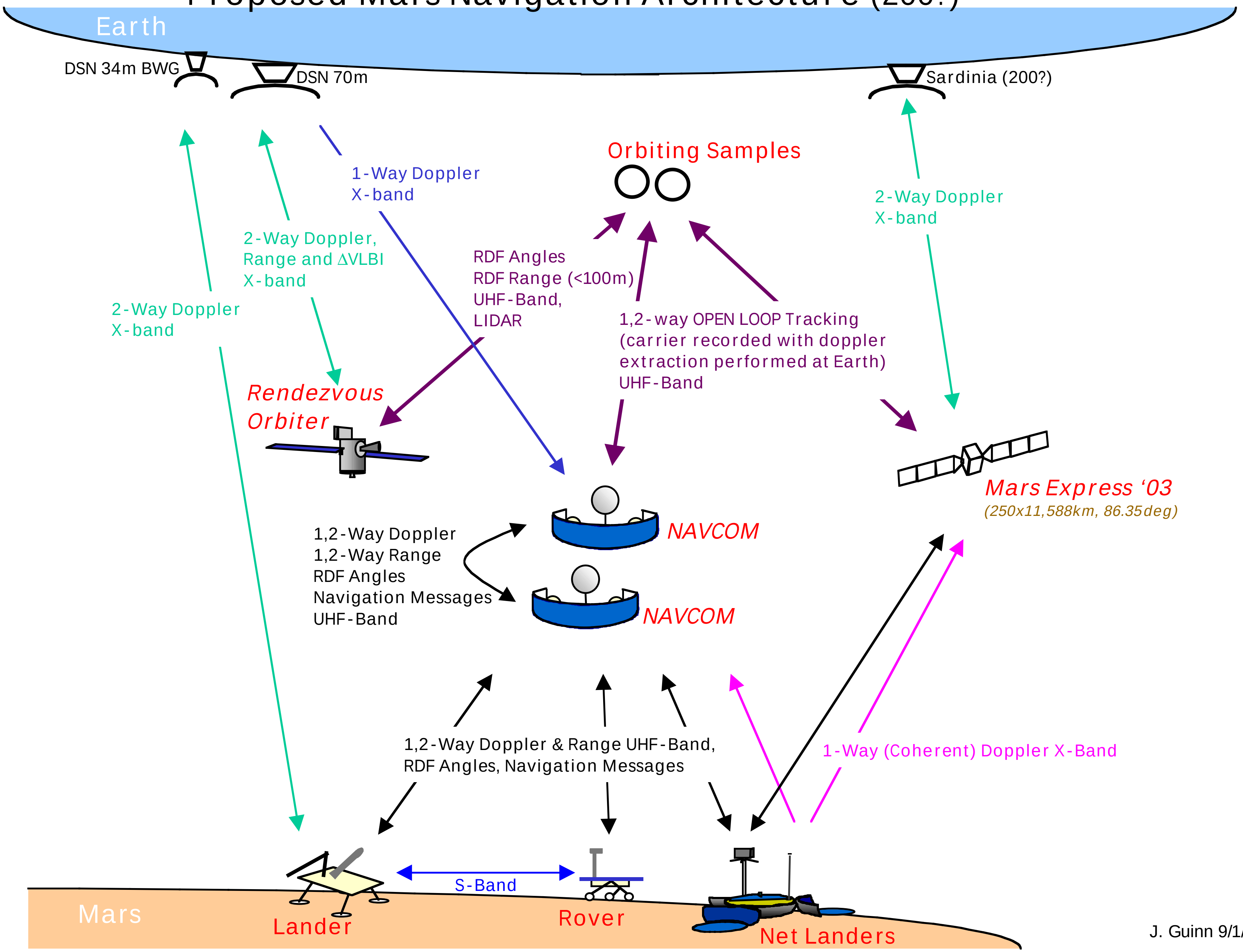
Proposed Mars Navigation Architecture (Radio Tracking Only)



Proposed Mars Navigation Architecture (200?)



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Network Design Drivers

Network designed for navigation and communication relay support

Maximum of six (6) operational Network orbiters

Network orbiters have highly stable frequency reference for autonomous self-navigation

Due to small number of Network orbiters, "GPS Like" kinematic orbit determination is accomplished with simultaneous observations (e.g., range & angles) from a single Network orbiter

Network Navigation Functions

User Services

In-Situ Radio Frequency Tracking

1 and 2-way UHF-Band Doppler and Range

1 and 2-way Open Loop Carrier Recording

Radio Direction Finding (RDF) Angles (not available with prototype Network orbiter)

Traditional Earth-Based Navigation

Collect radio frequency tracking observations, package in Network Observables Message (NOM) and send to Earth for user state determination by ground controllers. Solutions are distributed via a standard User State Message (USM).

Network Determined Navigation

User states determined autonomously by the Network and distributed via a standard User State Message (USM).

User Determined Navigation

User autonomously determines own state based on own measurements or with standard Network Observables Messages (NOM) and Network Almanac Messages (NAM).

In-Situ Time Synchronization Via Distribution of Network Time

Network Self-Navigation

DSN Radio Frequency Tracking

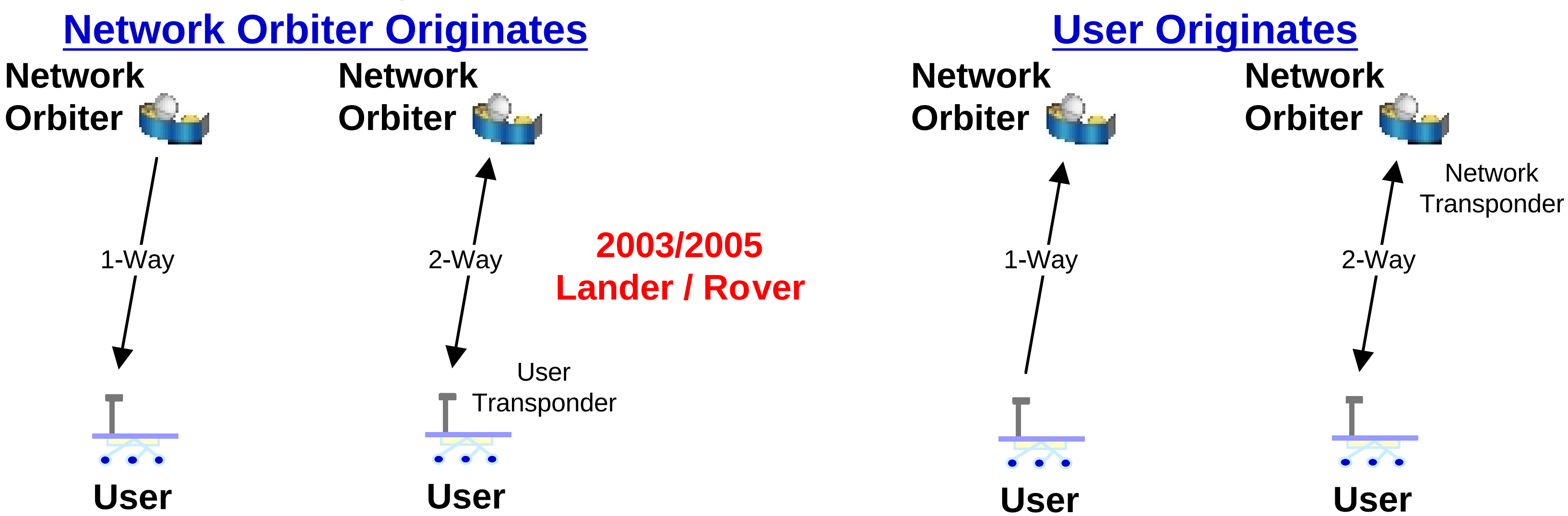
1-way X-Band Doppler

1-way UHF-Band Crosslinks

Autonomous Orbit Determination in Network Orbiter Transceiver CPU

In-Situ Radio Frequency Tracking

Doppler and Range Observations

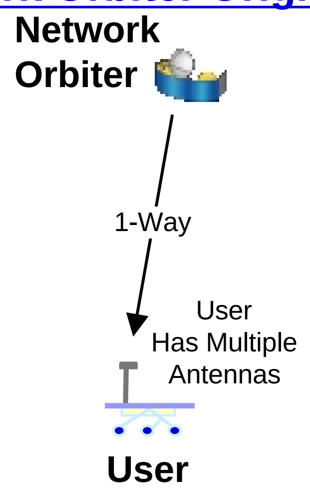


Open Loop Recording

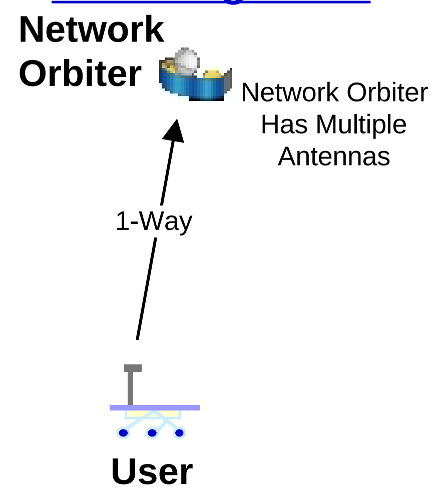
In-Situ Radio Frequency Tracking (cont.)

Radio Direction Finding (RDF) Angle Observations

Network Orbiter Originates

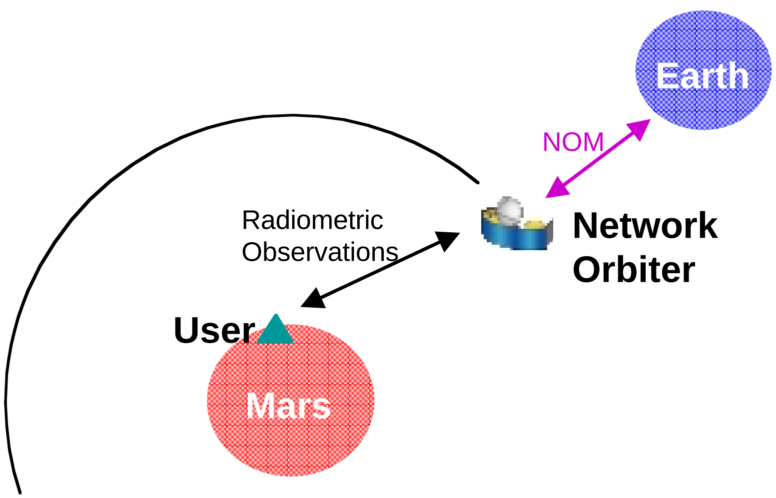


User Originates



Traditional Earth-Based Navigation

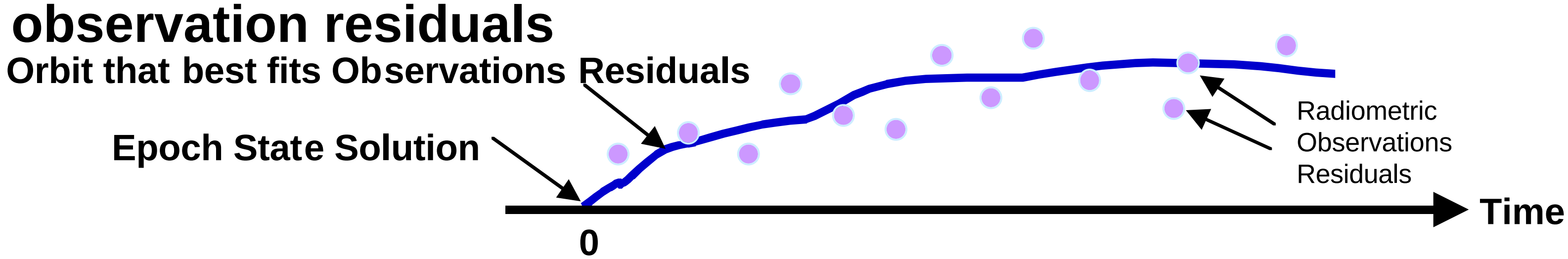
User states determined at Earth from tracking observations sent to Earth in Network Observation Messages (NOM)



Network Observables Message (NOM)
time_type = x, **time =** xxxx.xxx
transmitter_id = x, **receiver_id =** x,
observation_type = x, **observation =** xxxx.xxx

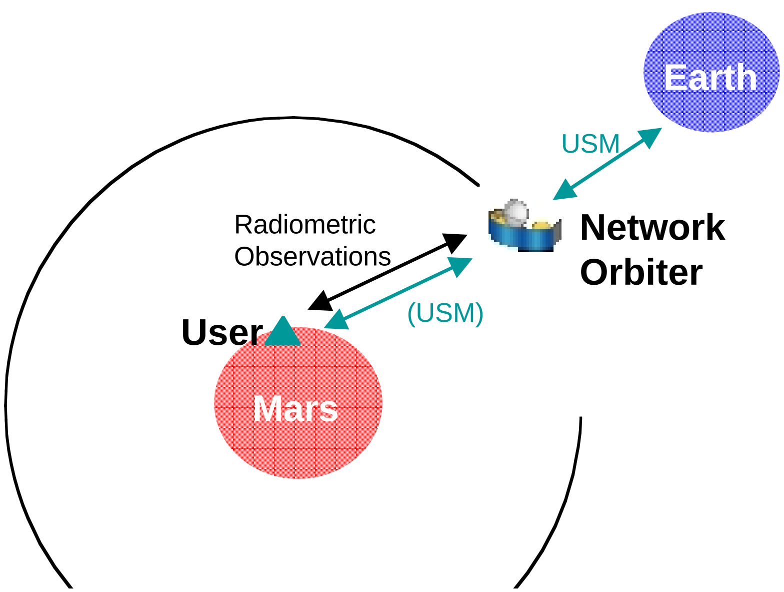
where: observation_type = 01 for 1-way phase
observation_type = 02 for 2-way phase
observation_type = 11 for 1-way doppler
observation_type = 12 for 2-way doppler
observation_type = 21 for 1-way range
observation_type = 22 for 2-way range
observation_type = 51 for azimuth
observation_type = 52 for elevation

Batch least-squares estimation of user state that minimizes observation residuals



Network Determined Navigation

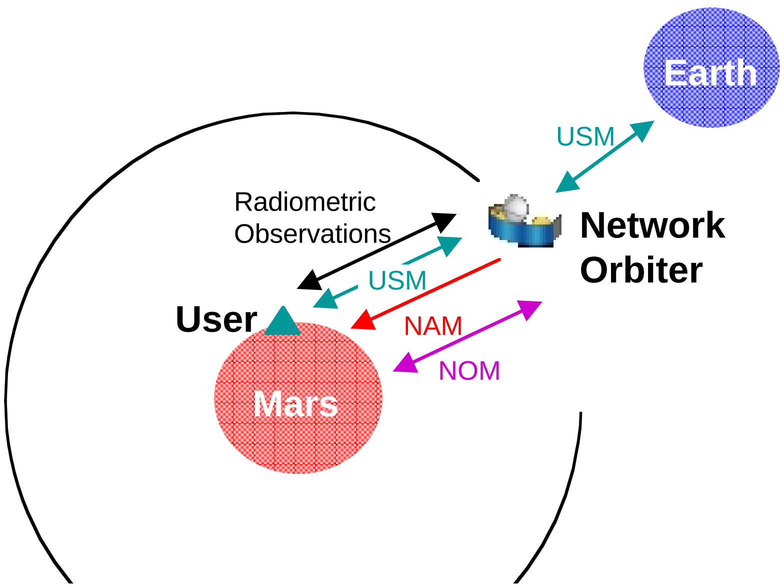
User states determined onboard a Network Orbiter from tracking observations and prior User State Messages (USM). Updated USM's are distributed to Users and to Earth.



User State Message (USM)
User_ID = x
EPOCH = xxxx.xxx
X = xxxx.xxx
Y = xxxx.xxx
Z = xxxx.xxx
DX = xxxx.xxx
DY = xxxx.xxx
DZ = xxxx.xxx
COVARIANCE = xxxx.xxx,xxx…
Clock Parameters= xxxx.xxx
QUALITY FLAGS = x,x,x...

User Determined Navigation

User determines own state from tracking observations, prior USM's and Network Almanac Messages (NAM). Updated USM's are distributed to Earth.



Network Almanac Message (NAM)
NODE_ID = x
EPOCH = xxxx.xxx
X_{NO} = xxxx.xxx
Y_{NO}= xxxx.xxx
Z_{NO} = xxxx.xxx
DX_{NO} = xxxx.xxx
DY_{NO} = xxxx.xxx
DZ_{NO} = xxxx.xxx
Clock Parameters$_{NO}$ = xxxx.xxx
COVARIANCE$_{NO}$ = xxxx.xxx,xxx...
QUALITY FLAGS = x,x,x...

Message Format Heritage

Observation Message Derived from:

DSN TRK215A - Raw uncalibrated data
DSN TRK218 - Orbit Data File (O DF)
DSN TRK225 - Archive format
DSN TRK234 - New Proposed format
RINEX-2 GPS Data format
Others

Navigation State and Almanac Messages Derived from:

SP1 and SP3 GPS Ephemeris formats
SPK SPICE Kernel format
Others

Network Equipment and Outputs

Equipment

Radiometric Observables Generation

DSN - 1 station/pass per day:

- X-Band Doppler Counter for 1-Way DSN Originated Measurements
  - [random error: 0.1 mm/sec @ 60 sec (1σ)]
- X-Band Doppler Transponder for 2-Way DSN Originated Measurements

'03 Network Orbiter (Prototype):

- UHF-Band Doppler Counter for 1-Way User Originated or 2-Way Network Originated Measurements
  - [random error: 0.1 mm/sec @ 60 sec (1σ)]
- UHF-Band Range Extractor for 1-Way User Originated or 2-Way Network Originated Measurements
  - [random error: 1m @ 60 sec (1σ)]

'05 Network Orbiters and beyond, Prototype plus following enhancements:

- Doppler Transponder for User Originated 2-Way Measurements
- Ranging Transponder for User Originated 2-Way Measurements
- Three Antennas for Radio Direction Finding (RDF)
- RDF Angle System [random error: 7deg at ranges>3000km, 0.07deg at ranges<500km (3σ)]

Oscillator

10^{-13} Fractional Frequency Stability over 60 seconds

(Enables Autonomous Operations via 1-Way DSN support)

Outputs

User State Message (USM)

User State and Uncertainties (Covariance) and quality flags

Network Almanac Message (NAM)

All Network Orbiter States and Uncertainties(Covariances) and quality flags

For exchange between Network orbiters and users

Network Observables Message (NOM)

Network radiometric observations

Minimum User Equipment and Outputs

Equipment

Radiometric Observables Generation

With '03 Network Orbiter (Prototype):

- Doppler Transponder for Network Originated 2-Way Measurements

With '05 Network Orbiters and beyond, Prototype plus following Options:

- UHF-Band Doppler Counter for 1-Way Network Originated or 2-Way User Originated Measurements
- UHF-Band Range Extractor for 1-Way Network Originated or 2-Way User Originated Measurements
- Ranging Transponder for Network Originated 2-Way Measurements
- Three Antennas for Radio Direction Finding (RDF)

Oscillator

10^{-9} Fractional Frequency Stability over 60 seconds

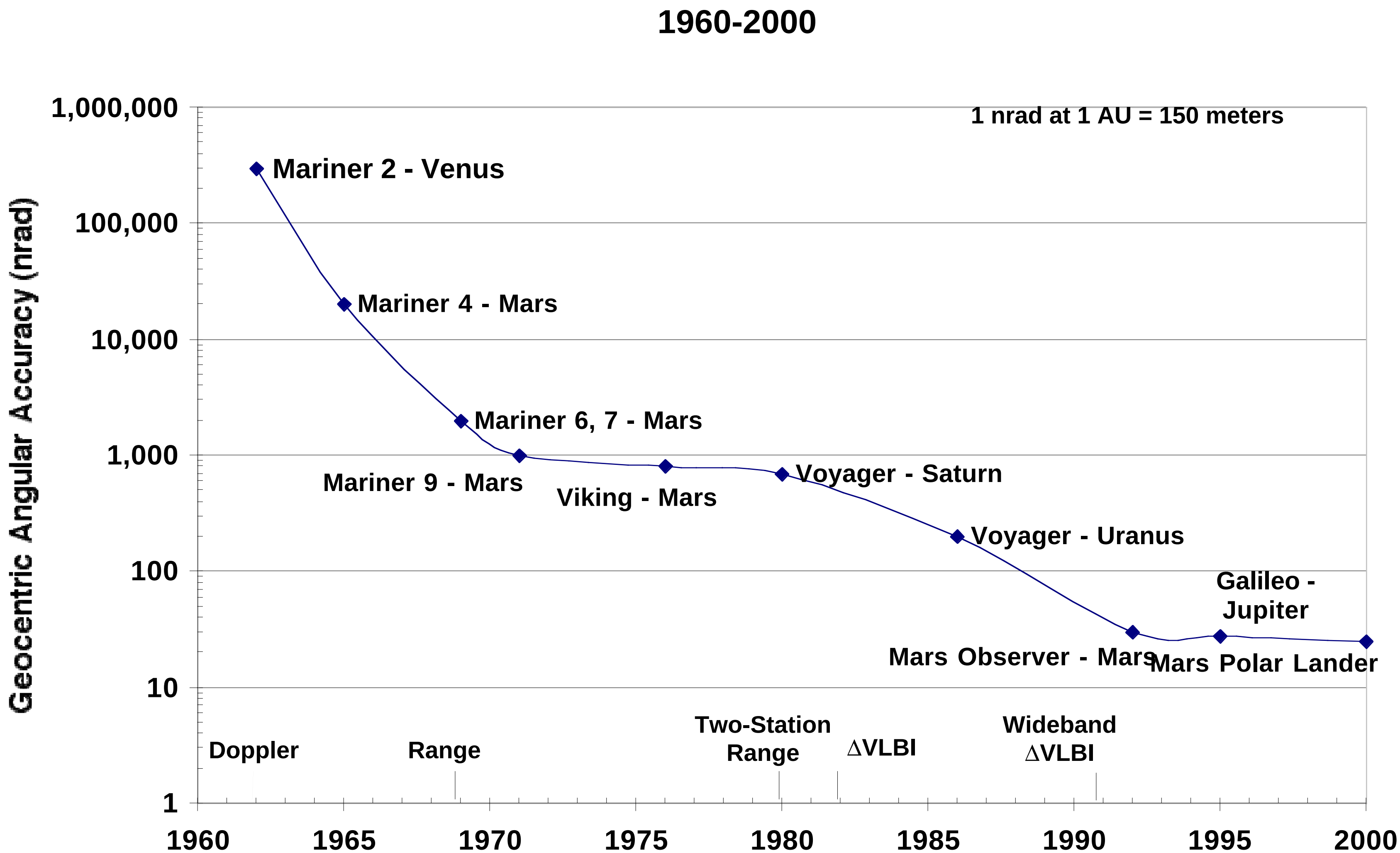
10^{-13} (Enables 2-Way accuracy with 1-Way Measurements)

Outputs

User State Message (USM) - OPTIONAL

User State and Uncertainties (Covariance) and quality flags

Evolution of DSN Navigation System Accuracy



PRELIMINARY (12/15/99)

Mars Approach Aerocapture/Landing Navigation Performance

Missions targeted near Mars Equator in 2003–2005

Entry Uncertainties (1σ)		4 Days Before Entry B-Plane Magnitude, Flight Path Angle	1 Day Before Entry B-Plane Magnitude, Flight Path Angle
DSN Doppler + Range Only	best	4.0 km, 0°.15	1.0 km, 0°.04
	worst	7.9 km, 0°.30	5.2 km, 0°.20
DSN Doppler + Range + ΔDOR	best	1.5 km, 0°.06	0.5 km, 0°.02
	worst	5.0 km, 0°.19	2.5 km, 0°.10
DSN Doppler + Range + Mars Infrastructure Orbiter* (Doppler Only)	best	1.0 km, 0°.04	0.2 km, 0°.01
	worst	6.0 km, 0°.23	1.0 km, 0°.04
Onboard Optical*	best	3.3 km, 0°.13	1.0 km, 0°.04
	worst	8.0 km, 0°.31	2.0 km, 0°.08

All ‘best’ cases assume 10% unmodelled dynamics, All ‘worst’ cases assume 30% unmodelled dynamics.

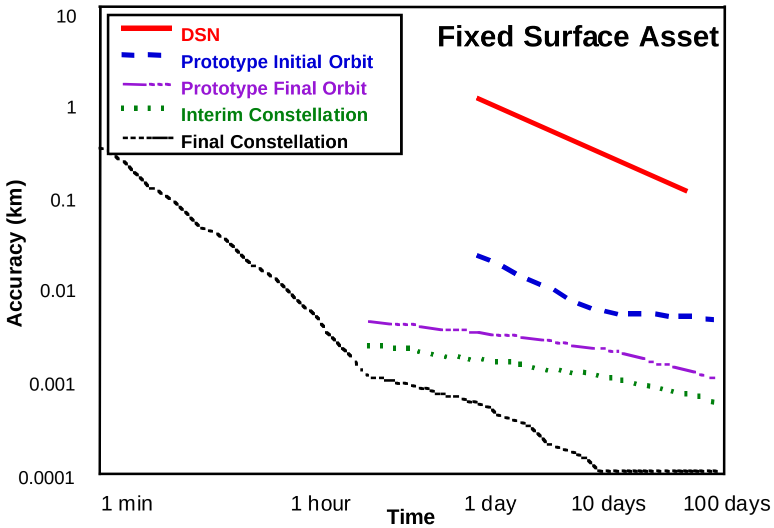
ΔDOR assumes no system biases

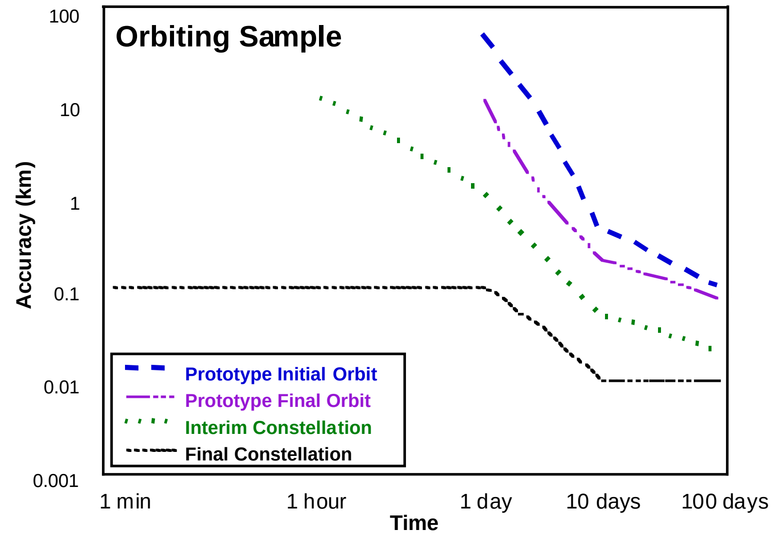
Infrastructure Orbiter in final low Mars orbit and assumes user has an USO or measurements are 2-way

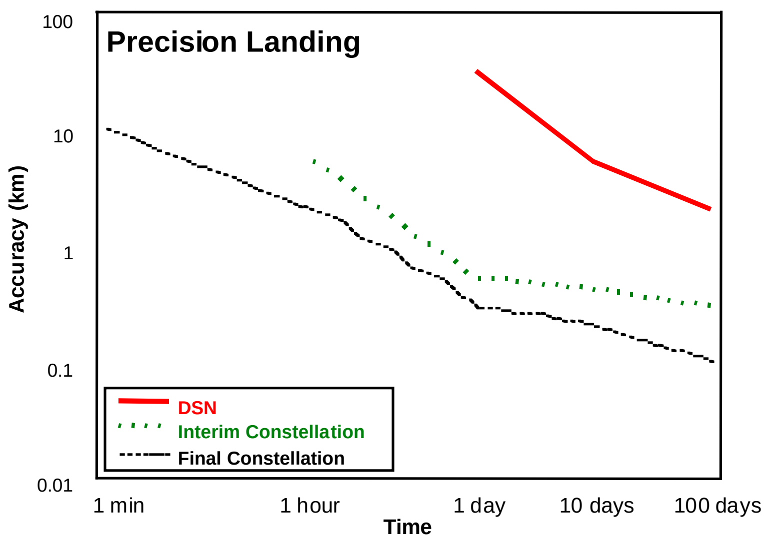
Optical ‘best’ assumes 12cm aperture camera (mass ≈ 1kg), Optical ‘worst’ assumes 5cm aperture camera

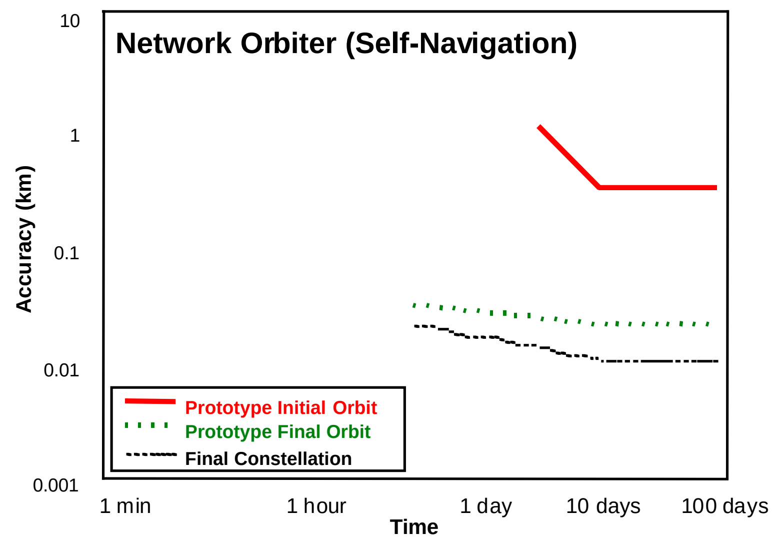
*Infrastructure Orbiter and Optical measurement systems also available for EDL support

Navigation Performance

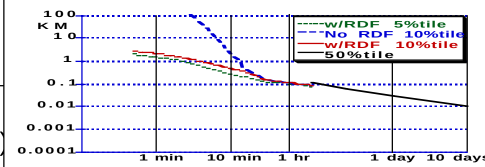
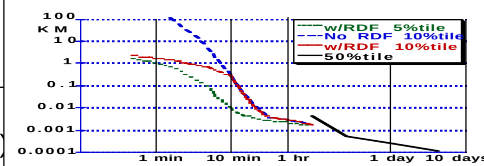
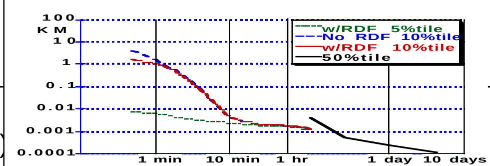
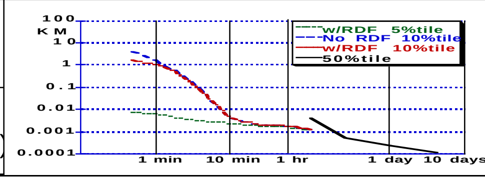








Navigation Performance (cont.)

Network Positioning Services				
Type of User Xcvr	**Tracking Data[2]**	**Nominal Nav Processing Site**	**Positioning Accuracy[3,4]**	**Other Services**
RF tone transmitter	1-way doppler (30 cm/sec[1])	Network		
RF receiver; doppler counter	1-way doppler (30 cm/sec[1])	User (network ephemerides needed)		
RF tone and ranging transmitter	1-way range (clock estimated); 1-way doppler (30 cm/sec[1])	Network		Time synch
RF receiver; doppler counter; range extractor	1-way range (clock estimated); 1-way doppler (30 cm/sec[1])	User (network ephemerides needed)		Time synch
RF tone transponder[5]	2-way doppler (0.05 cm/sec)	Network		
RF Xcvr; doppler counter	2-way doppler (0.05 cm/sec)	User (network ephemerides needed)		
RF tone and ranging transponder	2-way range (1 m); 2-way doppler (0.05 cm/sec)	Network		
RF Xcvr; doppler counter; range extractor	2-way range (1 m); 2-way doppler (0.05 cm/sec)	User (network ephemerides needed)		
AFF Xcvr	dual 1-way range (1 m); dual 1-way doppler (0.05 cm/sec)	Network		Time synch
AFF Xcvr	dual 1-way range (1 m); dual 1-way doppler (0.05 cm/sec)	User (network ephemerides needed)		Time synch

[1] 10^{-9} User's frequency stability [2] Noise level based on 60-sec averaging [3] 0.1 cm Differential phase noise => 10^{-3} radians RDF accuracy

[4] Final contellation. 5%tile of users see two network satellites simultaneously. 10%tile near-real-time performance is based on observing a single network satellite [5] 03'/05' Lander/Rover

Common Assumptions

Orbits

Mars '01	Final	h=396x404 km,	i=93°
Mars Express ('03)	Final	h=250x11588 km,	i=86°
Network '03 Prototype	3 Sol	h=250x78029 km,	i=172°
Network '03 Prototype	1 Sol	h=250x33858 km,	i=172°
Network '03 Prototype	Final	h=796x804 km,	i=172°
Network '05a	Final	h=796x804 km,	i=172°
Network '05b	Final	h=796x804 km,	i=111°
Network '07a	Final	h=796x804 km,	i=172°
Network '07b	Final	h=796x804 km,	i=111°
Network '09a	Final	h=796x804 km,	i=111°
Network '09b	Final	h=796x804 km,	i=111°

Omni-directional Antenna Visibility (no vehicle blockage constraints)

Network Spacecraft Parameters

Mass = 100 kg

SRP Area = 2.5 m^2

2003 Mars Exploration Rover Assumptions

Location:

MER-A - between 15°S and 5°N
MER-B - between 5°S and 15°N

Minimum transmit/receive elevation angle: 10°

Maximum observation range (UHF radio has 100 Hz Bandwidth PLL that sweeps over 10kHz)

1-way Doppler: 50000 km
2-way Doppler: 50000 km

Tracking in darkness

Oscillator stability: 10^{-9} over 60 seconds

2003 ESA Beagle 2 Lander Assumptions

Location between 0°N and 10°S

Minimum transmit/receive elevation angle: 10°

Maximum observation range (UHF radio has 100 Hz Bandwidth PLL that sweeps over 10kHz)

1-way Doppler: 50000 km
2-way Doppler: 50000 km

Tracking in darkness

Oscillator stability: 10^{-9} over 60 seconds

2005 Mars Sample Return Orbiting Sample Assumptions

Location

Altitude: 500x500 km ±100 km
Eccentricity: circular ±0.035
Inclination: 45° ±1°

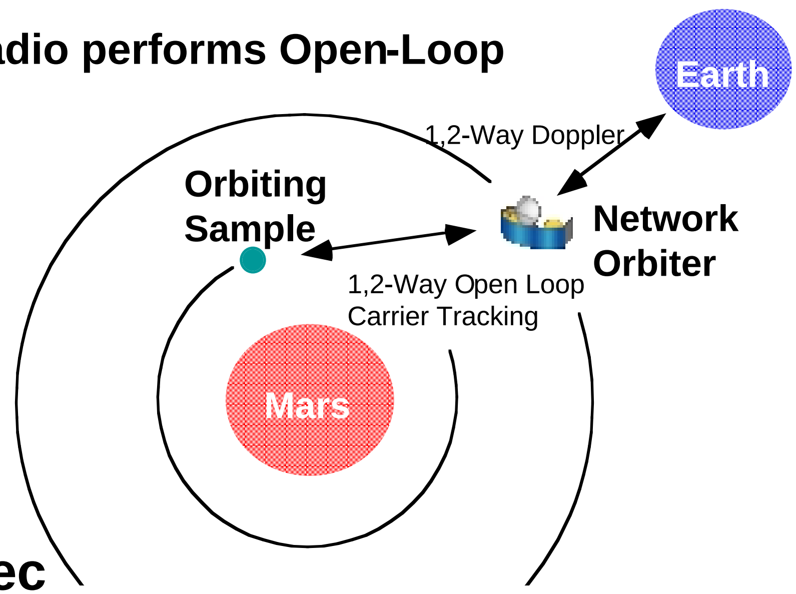
Maximum observation range (UHF Radio performs Open-Loop Tracking, a.k.a. "Canister Mode Tracking")

1-way Doppler: 5000 km
2-way Doppler: 1000 km

OS Spin Rate 20 RPM Maximum

Tracking in sunlight only

Oscillator stability: $3x10^{-7}$ over 60 sec



Netlander Assumptions

Location

LYcus Sulci	[LYS]:	130W	27.5N
MEnoMnia	[MEM]:	160W	12.5S
Tempe Terra South	[TTS]:	70W	35N
HEllas East	[HEE]:	275W	32.5S

Minimum transmit/receive elevation angle: 5°

UHF and X-Band for Ionosphere Delay Removal

Maximum observation range

1-way Doppler: 50000 km
2-way Doppler: 50000 km

Tracking in sunlight and shadow

Oscillator stability: 10^{-11} over 60 seconds